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An Intelligent Tutor for Diagnosing Faults in an Aircraft Power Distribution System

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Behavioral Technology Laboratories
University of Southern California

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An Intelligent Tutor for Diagnosing Faults in an Aircraft Power Distribution System

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13. ABSTRACT *(Maximum 200 words)*

A domain-general authoring system, DIAG, was employed to develop an intelligent tutor for diagnosing faults in a dual generator AC/DC power distribution system. The application provides an operable simulation of the front panel used to control power distribution in a dual engine aircraft, 148 replaceable units that comprise the functional elements of the target system, and a number of test points for performing fault isolation tests. In all, 105 faults are simulated for presentation to the learner.

Based entirely upon the model of the power distribution system, DIAG was able to generate context-specific advisement concerning 1) the effectiveness of the diagnostic strategy employed by an individual learner, 2) the rationality of the learner's suspicions considering the symptoms seen, and 3) recommended next steps to further isolate the simulated fault. The three most significant findings resulting from this development effort were that 1) no changes were required in the DIAG authoring system or intelligent advisement functions to implement this new and complex domain, 2) the instructional intelligence, in the form of generated dialogues, was produced automatically and required no acquisition or representation of human expertise, and 3) the application was produced in a very short time, approximately 22 man days.

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An Intelligent Tutor for Diagnosing Faults in an Aircraft Power Distribution System

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This work was performed under ONR contract N00014-97-1-0893, Susan Chipman Scientific Officer. Stephen Parchman, Training Specialist, Navy Personnel Research and Development Center, coordinated this work with the Naval Air Technical Training Center, Pensacola, Florida. Video taping at Pensacola was done with the assistance and cooperation of AEC (AW) Virgil Craven. Demonstrations and explanations of dual generator power distribution systems were provided by Petty Officer James Bell.

DIAG was developed using the tools of VIVIDS, a simulation authoring system developed under USAF funding, Jim Fleming of Armstrong Laboratory Scientific Officer, Allen Munro and Douglas Towne Principal Investigators. The AN77 multimeter used in this application was developed by Ken Roberts.

Background

Recent ONR funding supported the development of DIAG (Towne, 1997), a generic system for authoring intelligent tutoring of specific fault diagnosis tasks. During its development DIAG was employed to produce three intelligent diagnostic tutors, one for a portion of the SPY-1B Transmitter used in the AEGIS system, one for a small radio, and one for a home heating system. Each of these applications provided critical feedback that led to revisions and corrections as a normal part of the development process.

While each of the prototype applications provided extremely useful results, none represented a particularly challenging or realistic test of DIAG's capabilities. In addition, since each was developed concurrently with DIAG development, the authoring effort was highly confounded with DIAG development effort. As a result there was no clear indication of the effort required to produce a new application.

Objectives

The current project was undertaken to evaluate DIAG in terms of the authoring effort, the instructional intelligence, and the domain generality associated with producing a new highly complex application. An additional objective was to produce a useful application for Navy training. The primary objectives were attained via this application, as was the objective of producing a tutor for eventual Navy use.

This report is written to serve two purposes: 1) to document the findings of the development project, and 2) to provide a case study of a complex application, for future DIAG applicators.

The Application

The domain, selected by Stephen Parchman of the Navy Personnel Research and Development Center (NPRDC), San Diego, was that of dual generator AC/DC Power Distribution aboard military aircraft. This topic is one that is taught to a substantial number of Navy technicians, following training in basic electricity, generator theory, and related topics. At the Naval Air Technical Training Center (NATTC), Pensacola, Florida, a hardware-based training device, the 6E27, is employed. This training device,

measuring six feet wide by five feet high, allows an instructor to key in any of 73 possible faults which are then inserted into the system automatically. The student technician may then perform an operational checkout procedure, observe and record abnormal symptoms, confer with the instructor on possible causes of the abnormalities, and, if directed to, proceed to isolate the fault via use of test equipment.

The documentation of dual generator power distribution systems provided a listing of 19 significant 'fault complexes' – abnormal indications that express some problem with the aircraft's power, such as:

The right AC bus and right 26 VAC bus are de-energized during external power operation.

This abnormality may be caused by many possible faults. It is the essence of systems troubleshooting to identify those possible causes by analyzing the technical documentation of the system in terms of the learned function of each of the contributing operational units.

The technical documentation also included:
- a listing of 73 faults and the fault complexes each produced;
- illustrations of the front panel elements used to control power distribution;
- a detailed schematic diagram of the distribution system;
- some of the normal test point values.

Surprisingly, there was not a high level block diagram available; apparently instruction is conducted using the detailed schematic rather than any higher level representation.

Technical Approach

The first issue in designing the DIAG application was how closely to follow the system representation used by the existing 6E27 trainer . The advantages of maintaining that representation were that the existing Navy documentation could be used with the DIAG application, and the instructors would be fully familiar with the content of the DIAG application. The major advantage of making changes to that design would be that the presentation could be somewhat more realistic. The aircraft engines and generators, for example, could be shown realistically in DIAG, whereas in the 6E27 the engines were not shown and the generators were represented by rectangular units on the face of the trainer. Similarly, the 6E27 provides a toggle switch with which the student technician 'attaches' an external power source to the aircraft, whereas DIAG could provide a more realistic representation of that operation.

In spite of the limitations imposed by the 6E27's physical simulation as opposed to graphical simulation, the 6E27 front panel was generally an excellent portrayal of a dual generator power distribution system. It was decided, therefore, to follow that layout and representation. Interested parties could easily modify the DIAG application produced under this contract to make it more graphically realistic, if desired.

The second issue confronted during development was how to decompose an entire power distribution system so it could be represented conveniently on a single computer monitor. This decomposition was guided by considering the enabling objectives expressed in the laboratory work package for the course:

1 DOCUMENT the symptom of each fault discovered while performing an operation check of a dual generator AC/DC power distribution system in accordance with laboratory standards and safety procedures.

2 DETERMINE all probable faults for a malfunctioning dual generator AC/DC power distribution system.

3 ISOLATE each actual fault of a dual generator AC/DC power distribution system in accordance with laboratory standards and safety procedures.

(from Laboratory Work Package For Aviation Electrician's Mate Strand Course, Class A1, C-602-2039, Dual Generator AC/DC Power Distribution System, dated June 1995).

Using DIAG's hierarchy composition authoring tools, the graphical domain model was therefore structured into three main parts as follows:

1. a view of the front panel, for conducting the operational checkout procedure;
2. a view of the replaceable units, for identifying and replacing suspected units; and
3. a view of the available test points, for completing the fault isolation exercise.

The Development Process

The major steps performed in developing the DIAG application of the dual generator AC/DC power distribution system are now listed. These provide a good pattern for developing any DIAG application.

Step 1. Obtain improved views of the dual generator power distribution system.
Since the hard copy documentation was of limited visual quality and lacked color, it was necessary to obtain a much better representation of the elements of a power distribution system. Furthermore, it was necessary to actually understand dual generator AC/DC power distribution in order to make decisions about representing and simulating the domain. Consequently, a video tape was made at Pensacola of an instructor[1] performing and explaining the operational checkout procedure under normal conditions, and under each of the nineteen different fault complexes that had been identified. This required approximately three hours at the Pensacola facility.

Step 2. Produce a graphical representation of a dual generator power distribution system.
The top level screen shown in Figure 1 was created to indicate the three major sections of the simulation. Each of the three icons shown here would lead the user to a more detailed view of itself.

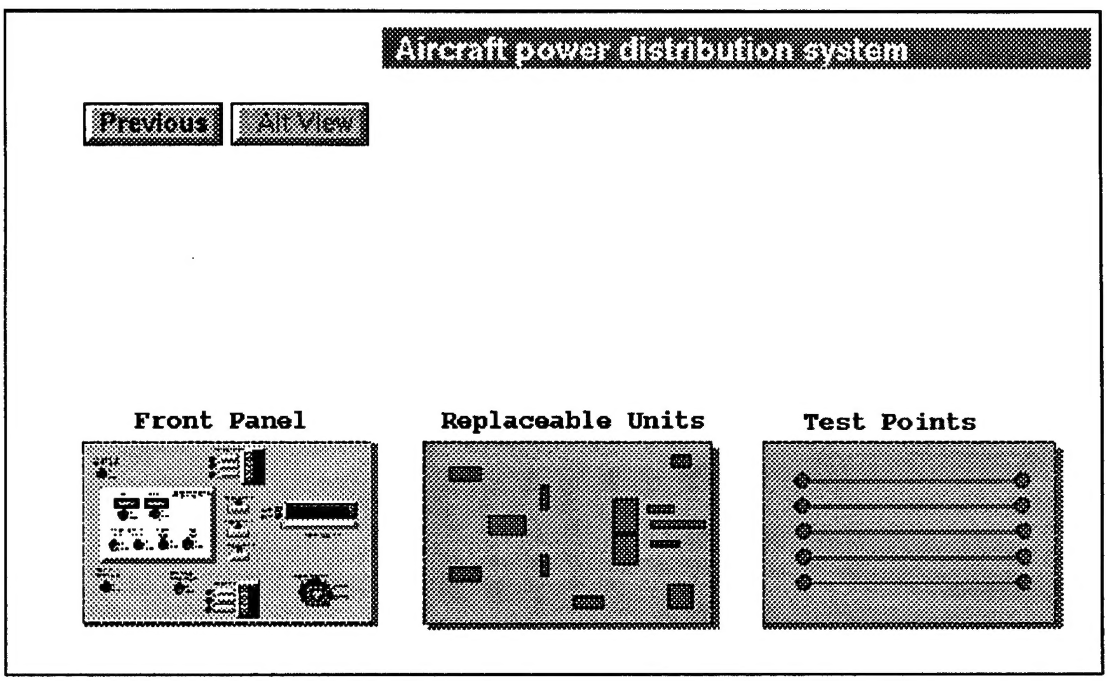

Figure 1. The Top Level DIAG Representation of Dual Generator AC/DC Power Distribution.
Next, more detailed views of each section were produced. Figure 2 presents the front panel view.

[1] Petty Officer James Bell

Next, more detailed views of each section were produced. Figure 2 presents the front panel view.

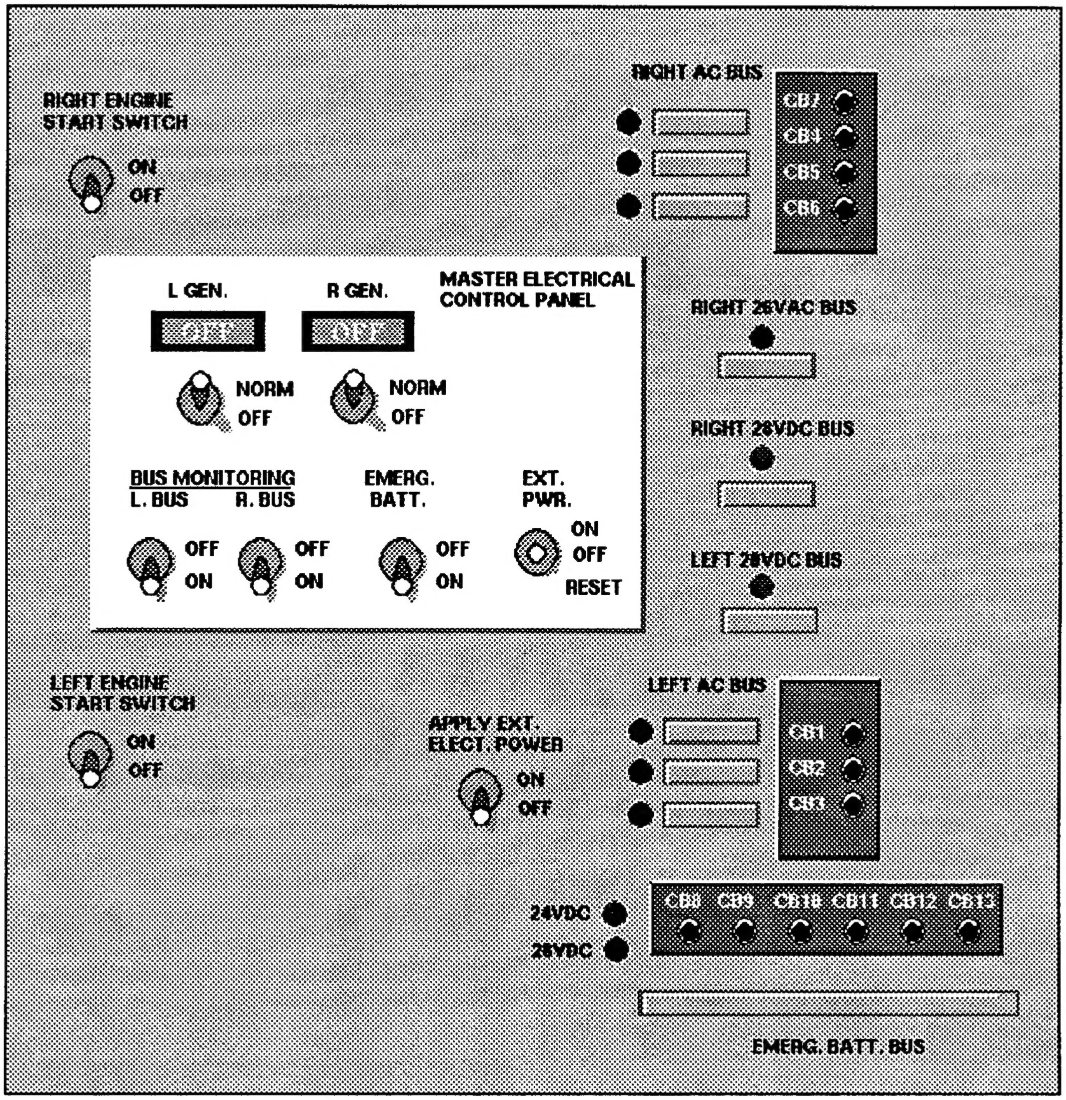

Figure 2. The Front Panel View

The front panel representation was produced primarily by copying a toggle switch, a two-state round indicator light, and a two-state rectangular indicator light from the DIAG Object Library to the screen. This brought into the application both a graphical representation of each object as well as the internal rules in the objects that allow it to function within DIAG without additional authoring effort. These objects were then duplicated, modified, and positioned, and panel labels were added, to produce the panel shown above.

At this stage, all switches and indicators on the front panel representation operated *individually*, i.e., all switches could be set via a mouse click and all indicators would respond graphically if their internal 'state' was manually set by the author. Rules to set indicator states would be added in steps 4 and 5, below.

Next the more detailed view of the replaceable units was produced as shown in Figure 3.

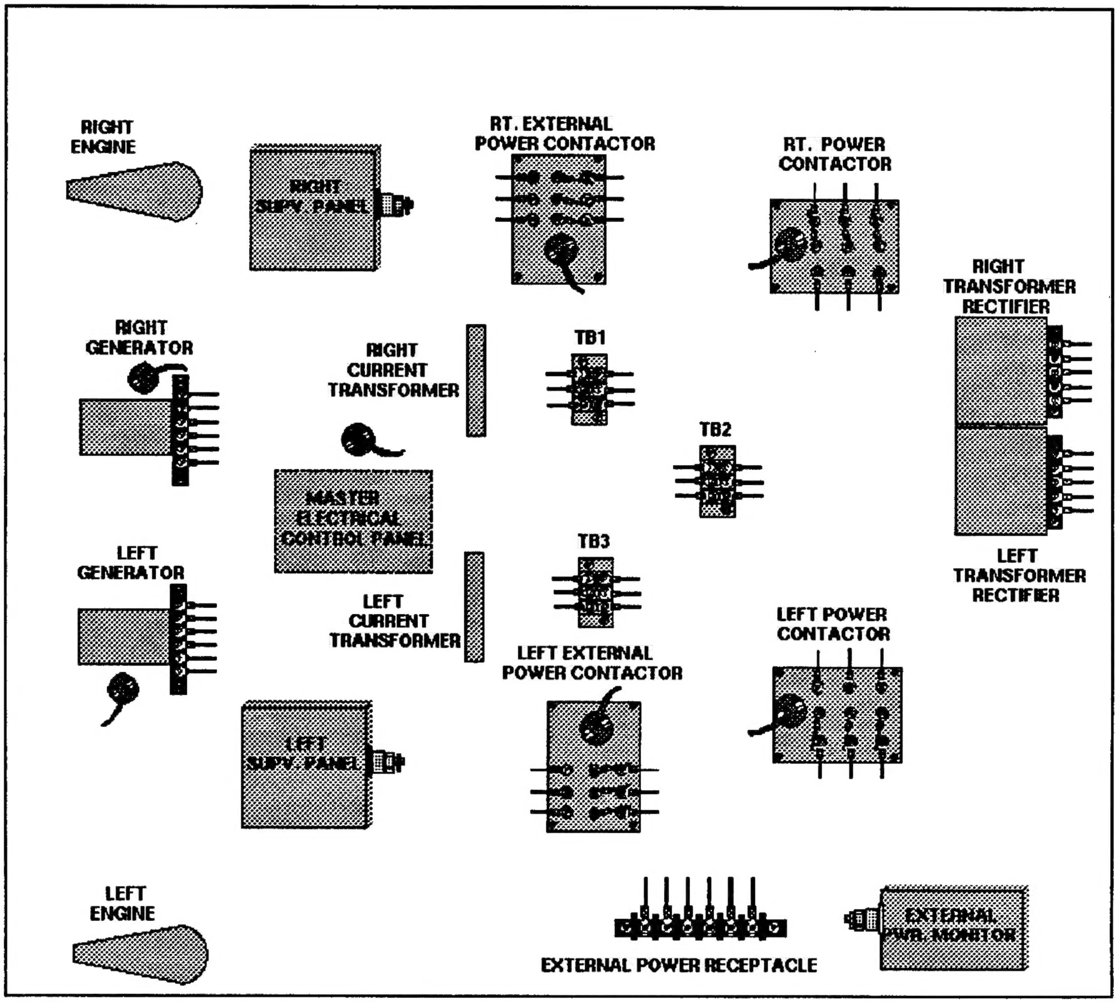

Figure 3. DIAG Representation of the Replaceable Units (partial).

Unlike the front panel, all of the graphical figures shown here are simply icons, each leading to a more detailed view when selected by the user.

Next, a more detailed view was produced for each of the 20 replaceable units of Figure 3. An example of one such view is shown in Figure 4. This screen presents one major replaceable unit, here the Right External Power Contactor, shown near the top center of Figure 3, along with a number of replaceable wires and connectors. The great majority of these 20 screens were produced rapidly by simply duplicating the wire object and the connector object shown in Figure 4.

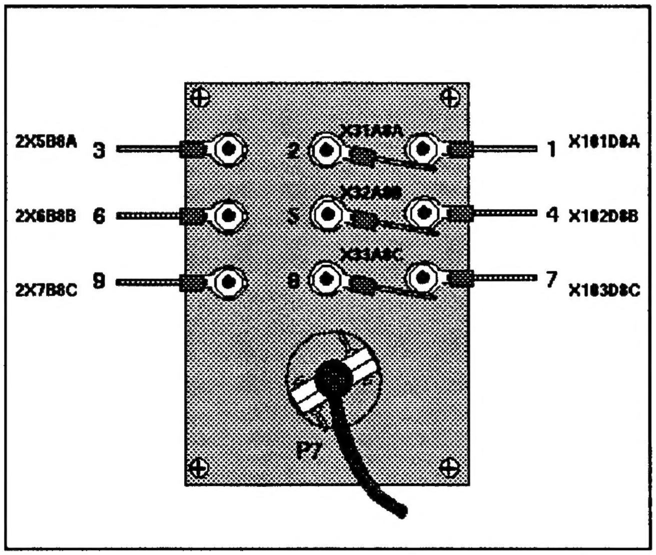

Figure 4. A Typical View of a Replaceable Unit: The Right External Power Contactor.

While developing the screen of Figure 3, it was determined that one screen could not adequately show all the replaceable units, even as icons. Therefore, another intermediate icon was included in Figure 3 to represent all the buses and breakers. Then the detailed view shown in Figure 5 was produced.

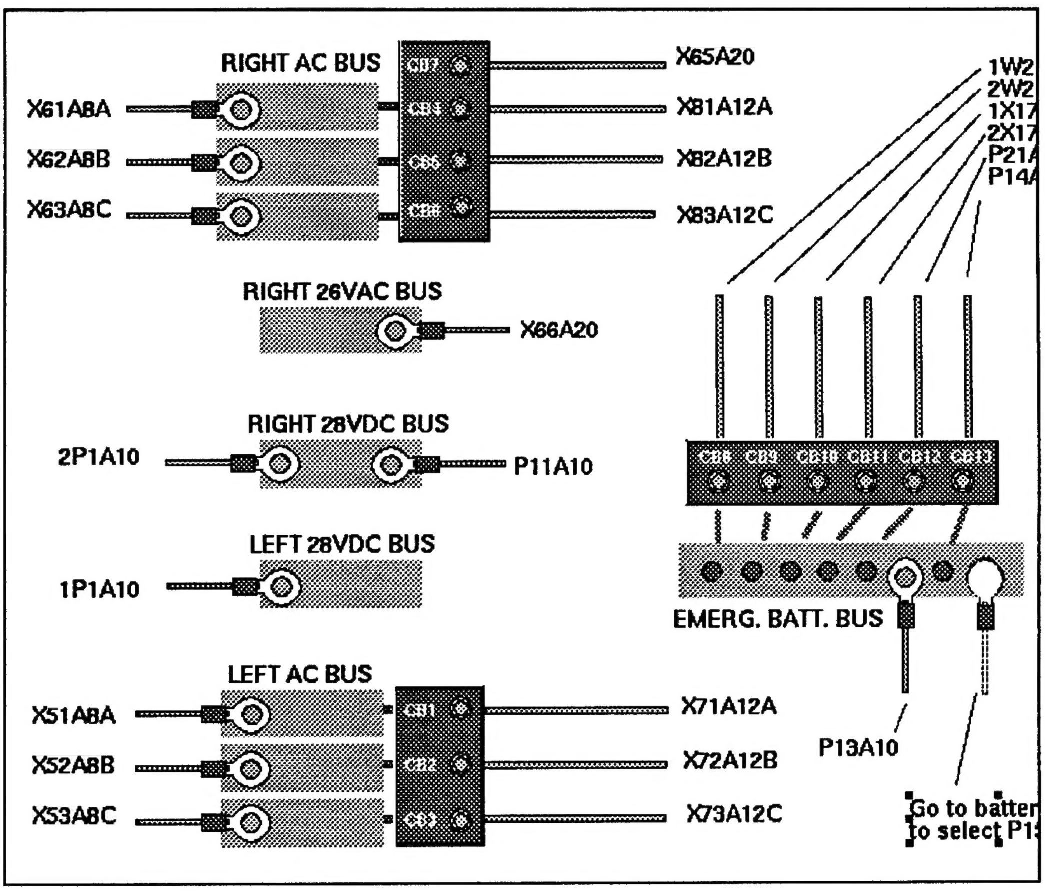

Figure 5. Breakers and Buses.

Finally, a screen view was produced in which the user would obtain test point readings (Figure 6). Here were shown all the individual wires that could be checked for continuity, their terminal test points, and a working multimeter, copied from the DIAG object library.

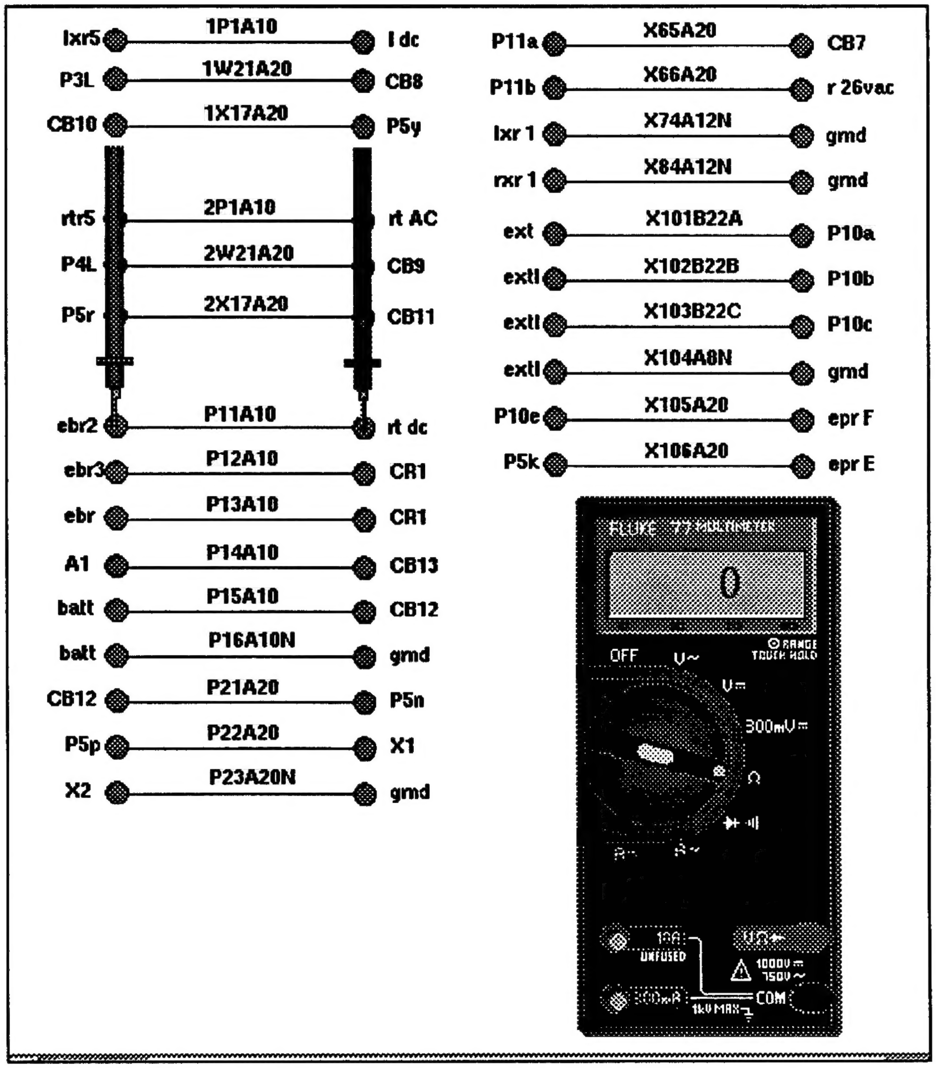

Figure 6. Test Points and Multimeter for Checking Continuity.

Step 3. Tag the Objects with Their DIAG Types.
For DIAG to function as an expert instructor and diagnostician it must know something about the purpose of each object in the model. To identify each object to DIAG, the author creates an attribute "objType" for each object and enters a value depending upon the object. Thus, all indicators carry the value "i" for objType, all replaceable units carry the value "r", and all iconic views that lead to more detail are tagged with "b" (for functional Block). This tagging permits DIAG to analyze a simulated system by noting the symptoms being presented in various modes of operation.

Appendix B lists the 148 replaceable units in the model of the power distribution system, appendix C lists the 26 indicators, and Figure 6 documents the test points provided.

Step 4. Make the Graphical Views into a Fully Operational System Model, for normal operation.
After the power distribution system was represented graphically, via 28 screen views, the functional model was made operational. This was done by entering a rule for the *state* attribute of each indicator and test point. Here, for example, is the rule that sets the state of the 24VDC light, shown in figure 2:

if .sbd.frontPanel.isBattPwrAvail then "ON" else "OFF"

This says that if the logical attribute *isBattPwrAvail* (is battery power available) is true, then the state of the 24VDC light is "ON", otherwise the state is "OFF". The prefix *.sbd.frontPanel* simply identifies to what object the rule is attached. The attribute *isBattPwrAvail* was created to reflect whether or not there was battery power available to the DC bus. This attribute is defined so that it is true if: 1) the emergency battery has been connected and 2) the Emergency Battery Switch is set to "ON".

In all, the model of dual generator power distribution required just 56 rules, one for each of the 26 indicators, one for each of the 25 continuity tests, plus 5 more useful intermediary rules such as the one for *isBattPwrAvail*, described above.

Step 5. Define the exercise faults and extend the indicator rules to incorporate abnormalities.
In this step the author specified each fault to be presented in a DIAG exercise. For this application, 105 faults were specified as listed in Appendix D. Note from Appendix D that failures were included in elements often omitted from maintenance training systems, such as in switches, indicators and circuit breakers.

To specify a fault the author selected a replaceable unit with the mouse, then keyed in an arbitrary code word that stands for the failure to be simulated, and a description of the problem that will be presented to the learner *after* the exercise is over. In appendix D, DIAG has entered the number of each replaceable unit in its index. For example, the first fault is a break in wire P15A10, which is the 107th replaceable unit in Appendix B. To have the DIAG model of the power distribution system act realistically when failed, the rules for normal operation were then extended to incorporate the possible failures. For example, the rule for *isBattPwrAvail*, shown above, was extended to include this third condition for truth:

not symptom1 and not symptom14 (i.e., neither fault code symptom1 nor symptom14 is true).

This says that for battery power to reach the DC bus, there must not be a failure inserted into the system model that exhibits failure complex 1 or 14. Now if DIAG inserts a fault that produces fault complex 14, for example, the attribute *isBattPwrAvail* goes to false, and the 24 VDC light goes off when it would normally be on.

Step 6. Define the modes of operation.
DIAG conducts its intelligent instruction in various predefined modes of operation, and it allows a user to set up a mode quickly by simply selecting a mode name. For this domain, these seven modes of operation were employed in the Operational Checkout Procedure:

mode name
Initial
Battery Connected
Emergency Battery Operation
External Power Operation
Left Generator Operation
Right Generator Operation
Dual Generator Operation

Each of these seven modes, detailed in Appendix E, was established in DIAG by keying in the mode name then setting the front panel controls as required for the mode.

Step 7. Define the training curriculum.
The author lists the problems that might be presented in instructional sessions. Associated with each fault is a short statement that is presented at the start of the exercise. Normally this statement is a problem report, such as "We're not getting any power out of the left generator." In this application, however, it was the training facility's desire to have the student technician determine all abnormalities by performing the operational checkout, therefore the opening statement simply advised the student to do so, and then to work with DIAG to identify the possible causes.

Step 8. Generate DIAG's symptom knowledge base.
For DIAG to reason intelligently about observed symptoms, it must have experience comparable to that which a human expert would amass from years of experience. To obtain this experience DIAG includes an analysis process that the author invokes by clicking a **Generate** button in the authoring dialog box. When this process is invoked, DIAG inserts each of the possible faults into the domain model, one at a time, in each defined mode, it simulates the effects of the faults by executing the *state* rules for the indicators, and it keeps track of the symptoms observed at each indicator. At the conclusion of this process DIAG has produced a frequency distribution which expresses the likelihood of observing each possible symptom when each of the replaceable units fails.

For this application there were 26 indicators, 7 modes, and 105 possible faults, which leads to 19,110 fault conditions to be analyzed and processed. This process, done on a 166 MHz 486 computer required four hours to complete. Since this step was only performed once, this time is tolerable. For most applications, however, the Generate step will be done more than once, since errors in symptoms caused by incorrect rules are usually discovered, and require that the **Generate** step be repeated following corrections. Consequently, a Pentium class machine is recommended at this stage, for large applications.

Development Product and Effort

The resulting training software simulates a generic aircraft dual generator AC/DC power distribution system operating normally and under 105 fault conditions. The system representation consists of 28 screens, including a fully operational front panel, 13 operational circuit breakers, 11 connectors, 94 failable wires, and 21 other failable components. Most of the latter components are large, complex units that can fail in a multitude of ways. In all, 148 replaceable units are represented.

DIAG either selects problems automatically or it follows a fixed problem presentation sequence, according to the specifications established in step 7, above. DIAG presents the initial problem statement, inserts the fault for the chosen problem, simulates the system as the learner works, and maintains records of the symptoms observed and what inferences an expert diagnostician would draw from those observations. When requested, DIAG generates discussions about selected symptoms or replaceable units, and it reviews and critiques the learner's suspicions at any stage.

The development effort, in man days, devoted to this application was as follows:

Step	Development Effort	Days
-	Study documentation and acquire initial system familiarity	3
1	Obtain improved views of the existing trainer (including travel)	3
-	Study tape and documentation to learn dual generator power distribution system	2
2	Produce a graphical representation of the system using DIAG objects and graphics	5
3	Tag the objects with their DIAG Types	1
4	Make the graphical views into an operational system model, for normal operation	3
5	Define the exercise faults and extend the indicator rules to incorporate abnormalities	3
6 & 7	Define the modes of operation and the training curriculum	1
8	Generate DIAG's symptom knowledge base and test system operation	1
	TOTAL MAN DAYS	22

Without question, the development effort was significantly eased by the documentation available for the existing 6E27 trainer. If that work had not been previously completed and available to this project, an additional one to two weeks of work would have been necessary to identify the key symptom complexes and the faults that produce them.

Although DIAG permits and facilitates manual entry of symptom likelihoods by experts, in this *project all symptom knowledge was generated automatically by DIAG.* A human expert in dual power distribution systems could, with a few days of effort, enhance DIAG's current knowledge base by manually revising the automatically generated symptom likelihoods for the 21 most complex replaceable units (e.g., generators, supervisory panels, power contactors, and so forth).

Results and Findings

The findings were as follows:

- The DIAG application was produced extremely rapidly, in spite of the complexity of the system and the number of elements included as possibly faulty. This is by far the most complex DIAG application produced. Availability of the DIAG object library significantly reduced the development effort.

- The hierarchical decomposition appears to provide convenient access to more detailed views, particularly since the hierarchy is only three levels deep.

- No changes were made to DIAG to accommodate this domain.

- One program change was made to improve the dual-probe continuity testing, which was found to be awkward. The improved process permits placement of the probes on two ends of wire with a single mouse click.

- DIAG's generic diagnostic reasoning correctly identifies the replaceable units most likely to produce the symptoms observed by the learner, and DIAG correctly tracks the learner's diagnostic performance.

- Just 56 rules were required to simulate the front panel indications and wire continuity tests under 105 fault possibilities. This was primarily due to the fact that the 105 faults produce just nineteen different system conditions.

- Interactive response time is poor on a sub-Pentium processor, as a result of the substantial processing done by DIAG in the background. For an application this size, DIAG requires a Pentium-level platform to deliver acceptable response.

- The system representation could be changed easily, without affecting any of the underlying functionality or diagnostic data, should future applicators wish to modify the realism of the graphics.

References

Towne, D. M. *Approximate Reasoning Techniques for Intelligent Diagnostic Instruction*, International Journal of Artificial Intelligence and Education, 1997.

Towne, D. M. *Intelligent Diagnostic Tutoring Using Qualitative Symptom Information*, in proceedings, American Institute for Artificial Intelligence, Intelligent tutoring System Authoring Tools, Nov, 1997.

Towne, D. M. *DIAG: Diagnostic Instruction and Guidance, Application Guide*. Los Angeles: Behavioral Technology Laboratories, University of Southern California, December, 1997.

Appendix A
Fault Complexes

The following 19 fault complexes were defined and documented by the developers of the 6E27 trainer, and were used in the DIAG application:

No.	Abnormality
1	Emergency battery bus de-energized when the emergency batter is connected
2	Left and right 28VDC buses de-energized during emergency battery operation
3	Left AC bus de-energized during left generator operation. Left generator warning light extinguished
4	Right AC bus and right 26 VAC bus de-energized during external power operation or left generator operation
5	Right AC bus and right 26 VAC bus de-energized during right generator operation. Right generator warning light extinguished
6	Right 26 VAC bus de-energized during external power operation, left or right generator operation, or dual generator operation
7	Left AC bus de-energized during external power operation or right generator operation.
8	Left AC bus de-energized during external power operation
9	Right AC bus and right 26 VAC bus de-energized during external power operation
10	Left generator warning light is illuminated during left generator operation. All buses de-energized except 24 VDC emergency battery bus when external power and right generator power is secured
11	Right generator warning light is illuminated during right generator operation. All buses de-energized except 24 VDC emergency battery bus when external power and left generator power is secured
12	All buses de-energized except the emergency battery bus during external power operation
13	Emergency battery bus does not receive 28VDC from the right 28VDC bus during external power operation, left or right generator operation, or dual generator operation. Right 28 VDC bus receives 24VDC from the emergency battery bus during emergency battery operation.
14	Emergency battery bus does not receive 28VDC from the right 28VDC bus during external power operation, left or right generator operation, or dual generator operation. Right 28 VDC bus and left 28VDC bus are de-energized during emergency battery operation.
15	CB8 trips when emergency battery is connected.
16	CB9 trips when emergency battery is connected
17	CB10 trips when emergency battery is connected
18	CB11 trips when emergency battery is connected
19	CB12 trips when emergency battery is connected

Appendix B
Replaceable Units

The following objects can be failed in DIAG exercises, they can be indicated as suspected by the learner or by DIAG, and they can be replaced by the learner when believed faulty.

1. right engine
2. left engine
3. right generator
4. connector P2
5. wire 2X10A18N
6. wire 2X9A18
7. wire 2X8A8N
8. wire 2X7A8C
9. wire 2X6A8B
10. wire 2X5A8A
11. left generator
12. connector P1
13. wire 1X5A8A
14. wire 1X6A8B
15. wire 1X7A8C
16. wire 1X8A8N
17. wire 1X9A18
18. wire 1X10A18N
19. right supervisory panel
20. connector P4
21. left supervisory panel
22. connector P3
23. connector P5
24. right engine Start switch
25. left engine Start switch
26. left generator switch
27. left generator switch
28. left Bus Monitor switch
29. right Bus Monitor switch
30. emergency Battery switch
31. external power switch
32. apply external Power switch
33. left generator warning light
34. right generator warning light
35. right Current Transformer
36. left Current Transformer
37. right external power contactor
38. connector P7
39. wire 2X5B8A
40. wire 2X6B8B
41. wire 2X7B8C
42. wire X31A8A
43. wire X32A8B
44. wire X33A8C
45. wire X101D8A
46. wire X102D8B
47. wire X103D8C
48. connector P6

49. left external power contactor
50. wire 1X5B8A
51. wire 1X6B8B
52. wire 1X7B8C
53. wire X41A8A
54. wire X42A8B
55. wire X101C8A
56. wire X102C8B
57. wire X103C8C
58. wire X101B22A
59. wire X101A8A
60. wire X102B22B
61. wire X103B22C
62. wire X104A8N
63. wire X106A20
64. wire X105A20
65. wire X102A8B
66. wire X103A8C
67. right power contactor
68. connector P9
69. wire 2X5C8A
70. wire 2X6C9B
71. wire 2X7C9C
72. wire X61A8A
73. wire X62A8B
74. wire X63A8C
75. wire X41A8A_2
76. wire X42A8B_2
77. wire X43A8C_2
78. left power contactor
79. connector P8
80. wire X31A8A_2
81. wire X33A8C_2
82. wire X51A8A
83. wire 1X5C8A
84. wire 1X6C8B
85. wire 1X7C8C
86. wire X52A8B
87. wire X53A8C
88. external power monitor
89. connector P10
90. right transformer rectifier
91. wire X84A12N
92. wire X81A12A
93. wire X82A12B
94. wire X83A12C
95. wire 2P1A10
96. left transformer rectifier
97. wire X74A12N
98. wire X71A12A
99. wire X72A12B
100. wire X73A12C
101. autoTransformer
102. connector P11

103. emergency battery relay
104. wire P22A20
105. wire P23A20N
106. emergency battery
107. wire P15A10
108. wire P16A10N
109. CR1
110. wire P12A10
111. wire X61A8A_2
112. wire X62A8B_2
113. wire X63A8C_2
114. wire X66A20
115. wire 2P1A10_2
116. wire P11A10_2
117. wire 1P1A10_2
118. wire X51A8A_2
119. wire X52A8B_2
120. wire X53A8C_2
121. CB7
122. CB4
123. CB5
124. CB6
125. CB1
126. CB2
127. CB3
128. CB8
129. CB9
130. CB10
131. CB11
132. CB12
133. CB13
134. wire X71A12A_2
135. wire X72A12B_2
136. wire X73A12C_2
137. wire P13A10_2
138. wire P15A10_2
139. wire 1W21A20
140. wire 2W21A20
141. wire 1X17A20
142. wire 2X17A20
143. wire P21A20
144. wire P14A10_2
145. wire X65A20
146. wire X81A12A_2
147. wire X82A12B_2
148. wire X83A12C_2

Appendix C
Indicators

(indicator number, name, and states)

1. left Generator Warning Light OFF ON
2. right Generator Warning Light OFF ON
3. right AC Bus Light_phaseA OFF ON
4. right AC Bus Light_phaseB OFF ON
5. right AC Bus Light_phaseC OFF ON
6. left AC Bus Light_phaseA OFF ON
7. left AC Bus Light_phaseB OFF ON
8. left AC Bus Light_phaseC OFF ON
9. right 26VAC Bus Light OFF ON
10. right 28VDC Bus Light OFF ON
11. left 28VDC Bus Light OFF ON
12. 24VDC light OFF ON
13. 28VDC light OFF ON
14. CB1 out in
15. CB2 out in
16. CB3 out in
17. CB7 out in
18. CB4 out in
19. CB5 out in
20. CB6 out in
21. CB8 out in
22. CB9 out in
23. CB10 out in
24. CB11 out in
25. CB12 out in
26. CB13 out in

Appendix D
Faults

(replaceable unit number, fault complex number, exercise recap text)

107 symptom1 Wire P15A10 was open, preventing the emergency battery bus from being energized when the emergency battery was connected.
108 symptom1 Wire P16A10N was open, preventing the emergency battery bus from being energized when the emergency battery was connected.
106 symptom1 The emergency battery provided no voltage, preventing the emergency battery bus from being energized when the emergency battery was connected.
132 symptom2 CB12 was open, causing both 28VDC buses to be de-energized during emergency battery operation.
133 symptom2 CB13 was open, causing both 28VDC buses to be de-energized during emergency battery operation.
144 symptom2 Wire P14A10 was open, causing both 28VDC buses to be de-energized during emergency battery operation.
143 symptom2 Wire P21A20 was open, causing both 28VDC buses to be de-energized during emergency battery operation.
30 symptom2 The Emergency Battery Switch was open, causing both 28VDC buses to be de-energized during emergency battery operation.
104 symptom2 Wire P22A20 was open, causing both 28VDC buses to be de-energized during emergency battery operation.
103 symptom2 The coil of the Emergency Battery Relay was open, causing both 28VDC buses to be de-energized during emergency battery operation.
105 symptom2 Wire P23A20N was open, causing both 28VDC buses to be de-energized during emergency battery operation.
23 symptom2 Connector P5 pin n was bad, causing both 28VDC buses to be de-energized during emergency battery operation.
21 symptom3 There was no 28VDC output from the left supervisory panel (K2's N.O. contacts remained open).
22 symptom3 Connector P3, pin f was open, causing the left AC bus to be de-energized during left generator operation.
23 symptom3 Connector P5, pin f was open, causing the left AC bus to be de-energized during left generator operation
28 symptom3 The Left Bus Monitor Switch was open, causing the left AC bus to be de-energized during left generator operation
78 symptom3 Coil A of the Left Power Contactor was open, causing the left AC bus to be de-energized during left generator operation
79 symptom3 Connector P8, pin a, was open, causing the left AC bus to be de-energized during left generator operation
131 symptom4 CB11 was open, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation.
23 symptom4 Connector P5 was bad, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation
29 symptom4 The Right Bus Monitoring Switch was open, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation
20 symptom4 Wire 2X18A20 was open at connector P4, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation
19 symptom4 The n. c. contacts in K2 of the Right Sup. Panel were open, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation
68 symptom4 Wire 2X20A20N in Connector P9 was open, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation

67 symptom4 Coil B of the Right Power Contactor was open, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation
142 symptom4 Wire 2X17A20 was open, causing the right AC bus and right 26VAC bus to be de-energized in external and left generator operation
19 symptom5 The contacts in K2 of the Right Supv. Panel were open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
20 symptom5 Connector P4, pin f was open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
23 symptom5 Connector P5, pin s was open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
29 symptom5 The Right Bus Monitoring Switch was open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
68 symptom5 Pin a of P9 was open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
68 symptom5 Pin b of P9 was open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
67 symptom5 Coil "A" of the Right Power Contactor was open, causing the right AC bus and right 26VAC bus to be de-energized during right generator operation.
121 symptom6 CB7 was open, causing the right 26VAC bus to be de-energized except for emergency batter operation.
145 symptom6 Wire X65A20 was open, causing the right 26VAC bus to be de-energized except for emergency batter operation.
114 symptom6 Wire X66A20 was open, causing the right 26VAC bus to be de-energized except for emergency batter operation.
102 symptom6 P11 was not connected securely, causing the right 26VAC bus to be de-energized except for emergency batter operation.
101 symptom6 Winding A to B in the Autotransformer was open, causing the right 26VAC bus to be de-energized except for emergency batter operation.
130 symptom7 CB10 was open, causing the left AC bus to be de-energized during external power or left generator operation.
141 symptom7 Wire 1X17A20 was open, causing the left AC bus to be de-energized during external power or left generator operation.
78 symptom7 Coil B of the Left Power Contactor was open, causing the left AC bus to be de-energized during external power or left generator operation.
79 symptom7 Pin d of P8 was open, causing the left AC bus to be de-energized during external power or left generator operation.
21 symptom7 The contacts in K2 of the Left Supv. Panel were open, causing the left AC bus to be de-energized during external power or left generator operation.
22 symptom7 Pin n of P3 was open, causing the left AC bus to be de-energized during external power or left generator operation.
23 symptom7 Pin d of P5 was open, causing the left AC bus to be de-energized during external power or left generator operation.
28 symptom7 The Left Bus Monitoring Switch was open, causing the left AC bus to be de-energized during external power or left generator operation.
37 symptom8 The coil in the Right External Power Contactor was open, causing the left AC bus to be de-energized during external power operation.
38 symptom8 Pin a of P7 was open, causing the left AC bus to be de-energized during external power operation.
23 symptom8 Pin m of P5 was open, causing the left AC bus to be de-energized during external power operation.
49 symptom9 The coil in the Left External Power Contactor was open, causing the right AC bus and right 26 VAC bus to be de-energized during external power operation.
48 symptom9 Pin a of P6 was open, causing the right AC bus and right 26 VAC bus to be de-energized during external power operation.

23 symptom9 Pin l of P5 was open, causing the right AC bus and right 26 VAC bus to be de-energized during external power operation.
2 symptom10 The left engine (CSD) was running too slow, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
11 symptom10 The main armature winding of the left generator was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
11 symptom10 The exciter field of the left generator was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
26 symptom10 The left generator switch was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
21 symptom10 Coil K2 in the Left Supv. Panel was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
1 symptom11 The right engine (CSD) was running too slow, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
3 symptom11 The main armature winding of the right generator was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
3 symptom11 The exciter field of the right generator was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
19 symptom11 Coil K1 of the Right Supv. Panel was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
27 symptom11 The Right Generator Switch was open, which de-energized all buses except for the 24 VDC bus when the right generator and external power is secured.
31 symptom12 The External Power Switch was open, causing all buses to de-energize except the emergency battery bus during external power operation.
23 symptom12 Pin j of P5 was open, causing all buses to de-energize except the emergency battery bus during external power operation.
88 symptom12 The External Power Monitor was internally defective, causing all buses to de-energize except the emergency battery bus during external power operation.
89 symptom12 Pin d of P10 was open, causing all buses to de-energize except the emergency battery bus during external power operation.
64 symptom12 Wire X105A20 was open, causing all buses to de-energize except the emergency battery bus during external power operation.
63 symptom12 Wire X106A20 was open, causing all buses to de-energize except the emergency battery bus during external power operation.
58 symptom12 Wire X101B22A was open, causing all buses to de-energize except the emergency battery bus during external power operation.
60 symptom12 Wire X102B22B was open, causing all buses to de-energize except the emergency battery bus during external power operation.
61 symptom12 Wire X103B22C was open, causing all buses to de-energize except the emergency battery bus during external power operation.
62 symptom12 Wire X104A8N was open, causing all buses to de-energize except the emergency battery bus during external power operation.
103 symptom13 Contact "A3" of the Emergency battery relay was open, causing the right 28VDC bus to receive 24VDC from the emergency battery bus only during emergency battery operation.
110 symptom13 Wire P12A10 was open, causing the right 28VDC bus to receive 24VDC from the emergency battery bus only during emergency battery operation.
109 symptom13 CR1 was open, causing the right 28VDC bus to receive 24VDC from the emergency battery bus only during emergency battery operation.
137 symptom13 Wire P13A10 was open, causing the right 28VDC bus to receive 24VDC from the emergency battery bus only during emergency battery operation.
116 symptom14 Wire P11A10 was open, preventing the emergency battery bus from receiving 28VDC from the right 28VDC bus during external power operation, left or gith generator operation, or dual generator operation.

103 symptom14 Contact "A2" of the Emergency battery relay was open, preventing the emergency battery bus from receiving 28VDC from the right 28VDC bus during external power operation, left or gith generator operation, or dual generator operation.
21 symptom15 In K2 of the Left supv. panel, the n.c. contacts were shorted to ground between pins "K" and "L" of J3, causing CB8 to trip when the emergency battery is connected.
139 symptom15 Wire 1W21A20 was shorted to ground, causing CB8 to trip when the emergency battery is connected.
23 symptom15 Pin c of P5 was shorted to ground, causing CB8 to trip when the emergency battery is connected.
33 symptom15 The Left Generator Warning Light was shorted to ground, causing CB8 to trip when the emergency battery is connected.
22 symptom15 Pin j of P3 was shorted to ground, causing CB8 to trip when the emergency battery is connected.
140 symptom16 Wire 2W21A20 was shorted to ground, causing CB9 to trip when the emergency battery is connected.
19 symptom16 The contact of K2 in the Right Supv. Panel were shorted to ground, causing CB9 to trip when the emergency battery is connected.
20 symptom16 Pin k of P4 was shorted to ground, causing CB9 to trip when the emergency battery is connected.
23 symptom16 Pin v of P5 was shorted to ground, causing CB9 to trip when the emergency battery is connected.
34 symptom16 The Right Generator Warning Light was shorted to ground, causing CB9 to trip when the emergency battery is connected.
28 symptom17 The Left Bus Monitoring Switch was shorted to ground, causing CB10 to trip when the emergency battery is connected.
21 symptom17 The contacts of K2 in the Left Supv. Panel were shorted to ground, causing CB10 to trip when the emergency battery is connected.
22 symptom17 Pin h of P3 was shorted to ground, causing CB10 to trip when the emergency battery is connected.
23 symptom17 Pin d of P5 was shorted to ground, causing CB10 to trip when the emergency battery is connected.
79 symptom17 Pin d of P8 was shorted to ground, causing CB10 to trip when the emergency battery is connected.
78 symptom17 Coil "B" of the Left Power Contactor was shorted to ground, causing CB10 to trip when the emergency battery is connected.
141 symptom17 Wire 1X17A20 was shorted to ground, causing CB10 to trip when the emergency battery is connected.
142 symptom18 Wire 2X17A20 was shorted to ground, causing CB11 to trip when the emergency battery is connected.
19 symptom18 The contacts of K2 in the Right Supv. Panel were shorted to ground, causing CB11 to trip when the emergency battery is connected.
20 symptom18 Pin h of P4 was shorted to ground, causing CB11 to trip when the emergency battery is connected.
67 symptom18 Coil "B" of the Right power contactor was shorted to ground, causing CB11 to trip when the emergency battery is connected.
68 symptom18 Pin d of P9 was shorted to ground, causing CB11 to trip when the emergency battery is connected.
23 symptom18 Pin u of P5 was shorted to ground, causing CB11 to trip when the emergency battery is connected.
29 symptom18 The Right Bus Monitoring Switch was shorted to ground, causing CB11 to trip when the emergency battery is connected.
30 symptom19 The Emergency Battery Switch was shorted to ground, causing CB12 to trip when the emergency battery is connected.

23 symptom19 Pin n of P5 was shorted to ground, causing CB12 to trip when the emergency battery is connected.
143 symptom19 Wire P21A20 was shorted to ground, causing CB12 to trip when the emergency battery is connected.

Appendix E
Modes

```
(mode name
        switch name: switch setting
        switch name: switch setting
.
.
)

initial
   batteryConnector : "notConnected"
   emergencyBatterySwitch : "OFF"
   extlPwrSwitch : "OFF"
   applyExternalPowerSwitch : "OFF"
   leftEngineStartSwitch : "OFF"
   rightEngineStartSwitch : "OFF"
   leftGeneratorSwitch : "NORM"
   rightGeneratorSwitch : "NORM"
   leftBusMonitoringSwitch : "ON"
   rightBusMonitoringSwitch : "ON"

batteryConnected
   batteryConnector : "connected"
   emergencyBatterySwitch : "OFF"
   applyExternalPowerSwitch : "OFF"
   extlPwrSwitch : "OFF"
   leftEngineStartSwitch : "OFF"
   rightEngineStartSwitch : "OFF"

emergencyBatteryOpn
   batteryConnector : "connected"
   emergencyBatterySwitch : "ON"
   applyExternalPowerSwitch : "OFF"
   extlPwrSwitch : "OFF"
   leftEngineStartSwitch : "OFF"
   rightEngineStartSwitch : "OFF"

externalPowerOpn
   batteryConnector : "connected"
   emergencyBatterySwitch : "OFF"
   applyExternalPowerSwitch : "ON"
   extlPwrSwitch : "ON"
   leftEngineStartSwitch : "OFF"
   rightEngineStartSwitch : "OFF"

leftGeneratorOpn
   batteryConnector : "connected"
   emergencyBatterySwitch : "OFF"
   leftEngineStartSwitch : "ON"
   rightEngineStartSwitch : "OFF"
   leftGeneratorSwitch : "NORM"
   leftBusMonitoringSwitch : "ON"
```

rightGeneratorOpn

- batteryConnector : "connected"
- emergencyBatterySwitch : "OFF"
- leftEngineStartSwitch : "OFF"
- rightEngineStartSwitch : "ON"
- rightGeneratorSwitch : "NORM"
- rightBusMonitoringSwitch : "ON"

dualGeneratorOpn

- batteryConnector : "connected"
- emergencyBatterySwitch : "OFF"
- leftEngineStartSwitch : "ON"
- rightEngineStartSwitch : "ON"
- leftGeneratorSwitch : "NORM"
- leftBusMonitoringSwitch : "ON"
- rightGeneratorSwitch : "NORM"
- rightBusMonitoringSwitch : "ON"

Appendix F
Session Plan

fixed 600
wireP15A10 symptom1
initial
Do the operational check then indicate what things you suspect, including wires.
***
wireP14A10 symptom2
initial
Do the operational check then indicate what things you suspect, including wires.
***
leftPwrContr symptom3
initial
Do the operational check then indicate what things you suspect, including wires.
***
rightBusMonSwitch symptom4
initial
Do the operational check then indicate what things you suspect, including wires.
***
rightSupPanel symptom5
initial
Do the operational check then indicate what things you suspect, including wires.
***
CB7RU symptom6
initial
Do the operational check then indicate what things you suspect, including wires.
***
leftPwrContr symptom7
initial
Do the operational check then indicate what things you suspect, including wires.
***
rightExtlPwrContr symptom8
initial
Do the operational check then indicate what things you suspect, including wires.
***
leftExtlPwrContr symptom9
initial
Do the operational check then indicate what things you suspect, including wires.
***
leftGenerator symptom10
initial
Do the operational check then indicate what things you suspect, NOT including wires.
***
rightEngine symptom11
initial
Do the operational check then indicate what things you suspect, NOT including wires.
***
externalPowerSwitch symptom12
initial
Do the operational check then indicate what things you suspect, including wires.
***
emergencyBattRelay symptom13
initial

Do the operational check then indicate what things you suspect, including wires.
***
emergencyBattRelay symptom14
initial
Do the operational check then indicate what things you suspect, including wires.
***
wire1W21A20 symptom15
initial
Do the operational check then indicate what things you suspect, including wires.
***
wire2W21A20 symptom16
initial
Do the operational check then indicate what things you suspect, including wires.
***
leftBusMonSwitch symptom17
initial
Do the operational check then indicate what things you suspect, including wires.
***
rightSupPanel symptom18
initial
Do the operational check then indicate what things you suspect, including wires.
***
wireP21A20 symptom19
initial
Do the operational check then indicate what things you suspect, including wires.
***